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European climate response to tropical volcanic eruptions over the last half millennium

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[1] We analyse the winter and summer climatic signal following 15 major tropical volcanic eruptions over the last half millennium based on multi-proxy reconstructions for Europe. During the first and second post-eruption years we find significant continental scale summer cooling and somewhat drier conditions over Central Europe. In the Northern Hemispheric winter the volcanic forcing induces an atmospheric circulation response that significantly follows a positive NAO state connected with a significant overall warm anomaly and wetter conditions over Northern Europe. Our findings compare well with GCM studies as well as observational studies, which mainly cover the substantially shorter instrumental period and thus include a limited set of major eruptions. **Citation:** Fischer, E. M., J. Luterbacher, E. Zorita, S. F. B. Tett, C. Casty, and H. Wanner (2007), European climate response to tropical volcanic eruptions over the last half millennium, *Geophys. Res. Lett.*, *34*, L05707, doi:10.1029/2006GL027992.

1. Introduction

[2] Explosive volcanism represents an important natural radiative forcing. Understanding how much of the observed climate variability at continental and seasonal scale is a response to natural and anthropogenic radiative forcing, as opposed to internal variability is a fundamental challenge and a crucial test for climate models attempting to predict future climate variations [e.g., *Shindell et al.*, 2003; *Stenchikov et al.*, 2002]. Volcanic eruptions offer an opportunity to test the climate response because their forcing is large and short lived. Volcanic aerosols injected into the lower stratosphere by explosive eruptions produce a substantial perturbation of the Earth's radiative balance, causing stratospheric warming and tropospheric cooling at the same time. Strongly enhanced scattering of incoming solar radiation causes global annual cooling at the surface for typically 2 to 3 years [*Sear et al.*, 1987; *Robock and Mao*, 1995; *Mann et al.*, 1998; *Crowley and Kim*, 1999; *Crowley et al.*, 2000; *Hegerl et al.*, 2003; *Jones et al.*, 2004]. Clustering of major eruptions may even represent a substantial climate forcing over decadal to multi-centennial timescales [e.g., *Crowley*, 2000].

[3] Analysis of observational data indicate that over higher latitudes of Northern Hemispheric (NH) land regions radiative cooling following eruptions is dominant only in the summer half-year, whereas anomalously warm conditions prevail during boreal winters [*Groisman*, 1992; *Robock and Mao*, 1992; *Kelly et al.*, 1996; *Shindell et al.*, 2004]. GCM studies suggest that the winter warming is produced by atmosphere-dynamical effects in form of a positive phase of the Arctic Oscillation/North Atlantic Oscillation (AO/NAO) [e.g., *Graf et al.*, 1994; *Shindell et al.*, 2001; *Stenchikov et al.*, 2002, 2006]. The positive phase of the AO/NAO is induced by an enhancement of the stratospheric meridional temperature gradient caused by radiative heating in the aerosol cloud over the tropics [*Kodera*, 1994; *Kirchner et al.*, 1999]. *Stenchikov et al.* [2002] further proposed that ozone depletion as well as the tropospheric cooling effect of aerosols contribute to a positive AO/NAO [see also *Yoshimori et al.*, 2005].

[4] In this study we present new evidence on the seasonal European temperature and precipitation response as well as the circulation anomalies related to 15 major tropical volcanic eruptions. Independent (i.e. sharing no common predictors in the reconstructions) seasonally resolved reconstructed land surface temperature, precipitation and geopotential height fields covering the last centuries are analysed to determine the mean response to eruptions. The length of the reconstruction allows us to include a large set of major eruptions, where the forcing is undisputed, whereas some earlier studies included minor events where a clear response would not necessarily be expected. We thereby minimise the risk that the volcanic signal is obscured by other forcings and internal variability. Since the different reconstructions share no common predictors, we can rule out any circular statement in the comparison of the temperature, precipitation and circulation anomalies. Furthermore, to our knowledge, this is the first detailed analysis of the volcanic influence on high resolution mid-latitudinal precipitation patterns.

2. Data

2.1. Volcanic Data

[5] Fifteen major tropical volcanic eruptions are selected combining three measures of past volcanic activity, the Volcanic Explosivity Index (VEI) [*Newhall and Self*, 1982] (updated by *Simkin and Siebert* [1994]), the Ice core Volcanic Index (IVI) [*Robock and Free*, 1995] and an updated volcanic data set by *Ammann and Naveau* [2003] (see complete list of eruptions in Table 1). The most

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Table 1. Selected 15 Major Tropical Volcanic Eruptions of the Period 1500–2000 Used in This Study[a]

Volcano	Country	Dating	DJF YR0	JJA YR0	VEI	IVI	Source
Kelut	Indonesia	1586 su	1587	1587	5?	0.25	[1, 2]
Ruiz	Colombia	1595 au	1597	1596	4	0.25	[1, 2]
Huaynaputina	Peru	1600 sp	1601	1600	6	0.5	[1, 2]
Parker	Philippines	1641 wi	1642	1641	5?	0.4	[1, 2]
Gamkonora	Indonesia	1673 su	1674	1674	5?	0.2	[1, 2]
unknown[b]		1809??	1810	1809	?	0.75	[2]
Tambora[b]	Indonesia	1815 sp	1816	1816	7	1	[1, 2]
Galunggung[b]	Indonesia	1822 au	1824	1823	5	0.2	[1, 2]
Babuyan Claro[b]	Philippines	1831??	1832	1832	4?	0.3	[1, 2]
Cosiguina[b]	Nicaragua	1835 wi	1836	1835	5	0.3	[1, 2]
Krakatau[b]	Indonesia	1883 su	1884	1884	6	0.4	[1, 2]
Santa Maria[b]	Guatemala	1902 au	1904	1903	6?	0.25	[1, 2]
Agung[b]	Indonesia	1963 sp/su	1964	1964	5	0.2	[1, 2]
El Chichon[b]	Mexico	1982 sp/su	1983	1983	5	0.2	[1, 2]
Pinatubo[b]	Philippines	1991 sp	1992	1992	6	0.3	[1, 2]

[a]The year and season (if known) of the main eruption are indicated in column three. Column four and five shows our definition of winter (DJF) and summer (JJA) of year 0. Column six and seven indicate the volcanic indices VEI [*Newhall and Self*, 1982; *Simkin and Siebert*, 1994] and IVI [*Robock and Free*, 1995]. Column seven indicates the references used for the dating: [1] is *Simkin and Siebert* [1994] and [2] is *Ammann and Naveau* [2003].
[b]The 10 eruptions used for independent precipitation and geopotential height analysis.

important selection criterion is a high certainty of the eruption dating, since our statistical analysis is sensitive to uncertainties larger than a few months. All eruptions are based on historical records [*Simkin and Siebert*, 1994], except for the unknown 1809 eruption. This eruption was identified based on ice-core evidence [*Dai et al.*, 1991; *Yalcin et al.*, 2006; C. Gao et al., Atmospheric volcanic loading derived from bipolar ice cores accounting for the spatial distribution of volcanic deposition, submitted to *Journal of Geophysical Research*, 2007] and its climate impact has later been found in tree-ring data [*Briffa et al.*, 1998]. However, the signal could never be attributed undoubtedly to one specific volcanic eruption. We confined our selection to tropical eruptions since the winter response was shown to differ compared with extratropical eruptions [*Robock*, 2000, and references therein]. The eruptions are not evenly distributed over the time period, and cluster at the end of the 16th/early 17th century and in the first part of the 19th century. The change in background stratospheric aerosol loading is not directly accounted for in this study. However, since we analyse the relative response with respect to a 5-year pre-eruption period, it is expected to play a marginal role.

2.2. Climate Reconstruction Data

[6] Seasonally resolved reconstructed land surface temperature [*Luterbacher et al.*, 2004] (0.5° × 0.5° resolution, recalculated using only temperature predictors), precipitation [*Pauling et al.*, 2006] (0.5° × 0.5° resolution) and 500 hPa geopotential height fields [*Casty et al.*, 2005] (2.5° × 2.5° resolution) are used. The temperature and precipitation reconstructions are based on multi-proxy predictor information (long instrumental station series, documentary proxy evidence and natural proxies) and cover the period 1500–2000 (1769–2000 for precipitation). The quality of the precipitation reconstructions allows a meaningful analysis of the interannual signal only over a shorter period. The 500 hPa height reconstruction is based on station pressure series only and covers the period 1769–2000. The three different reconstructions use independent predictors, which allows us to test the significance of the temperature, precipitation and circulation response independently. Since the reconstruction methods were calibrated in periods with relatively weak volcanism the consistent response to eruptions increases our confidence in the robustness of our results.

3. Methods

[7] The data are expressed as seasonal departures from the 5-year pre-eruption period. The first three months following an eruption are not included in the analysis. Thus, the lag between an eruption and the summer or winter of year 0 may vary between 4 and 15 months. For example, summer of year 0 for the Tambora eruption is summer 1816. This time-lag has been selected since the conversion of SO_2 into sulphate aerosols takes several weeks [*Zhao et al.*, 1995] and the aerosols take some time to be transported to the mid-latitudes, particularly in the respective summer hemisphere [*Ammann et al.*, 2003]. Superposed epoch analysis is performed to identify the mean summer and winter response to large volcanic eruptions. This method has been widely used in studies of the volcanic effect on climate [*Panofsky and Brier*, 1958; *Sear et al.*, 1987; *Bradley*, 1988; *Adams et al.*, 2003]. Given enough samples the superposition isolates climatic signals by averaging out non-volcanic features.

[8] Statistical significance was determined gridpointwise using the two-sided Mann-Whitney test. We use the null hypothesis that the mean in the post-eruption period does not significantly differ from the mean in the 5-year pre-eruption period. The anomalies of post-eruption seasons are tested against non-volcanic seasons (defined as all seasons except the eight years following a major volcanic eruption).

4. Summer Cooling

[9] The average influence of 15 major volcanic eruptions over the last 500 years is a distinct European summer cooling during two post-eruption years. For the individual post-eruption episodes the timing of the maximum cooling

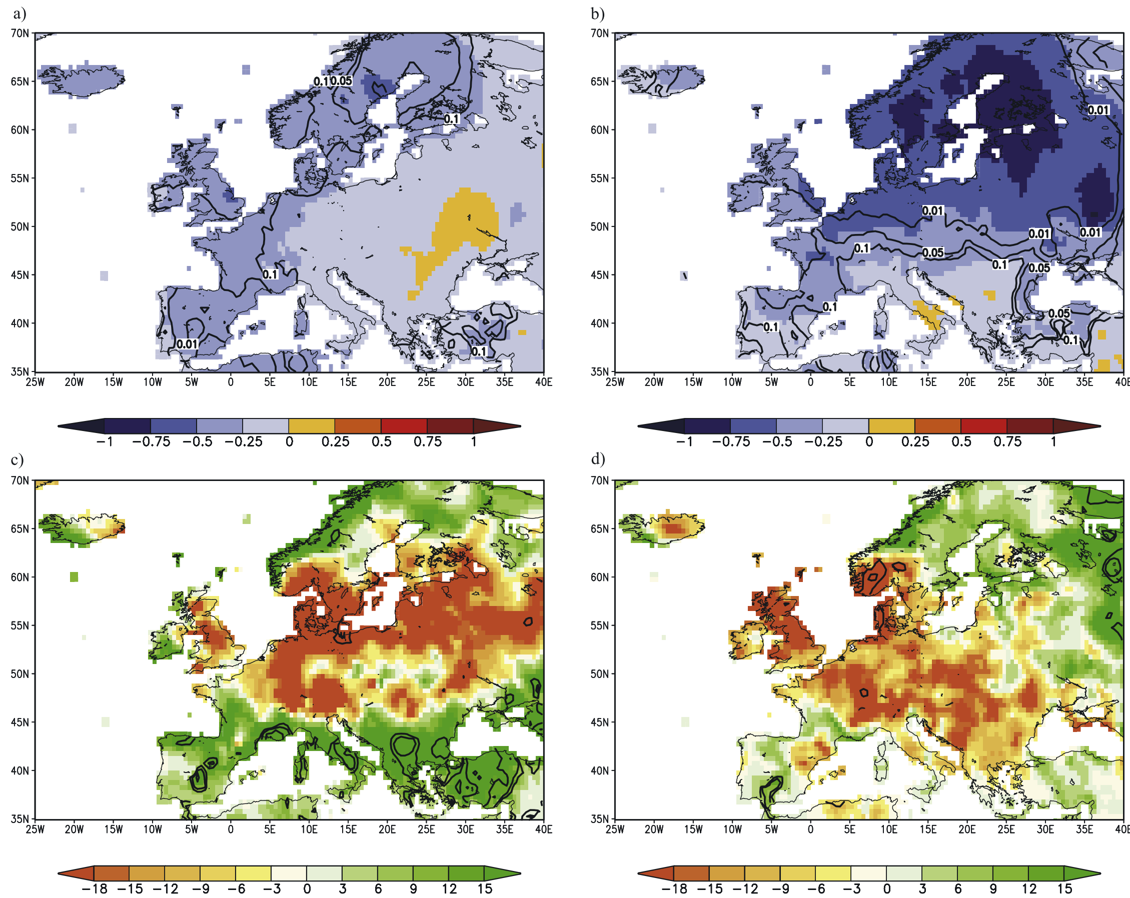

Figure 1. Anomaly composite of European summer temperature [°C] in (a) year 0 and (b) year 1 following 15 tropical volcanic eruptions over the past half millennium. (c and d) Same as Figures 1a and 1b but for precipitation [mm/month] following 10 eruptions. The black contours mark the statistical significance as p-values (representing 90%, 95% and 99% confidence level) of the Mann-Whitney Rank Sum Test.

varies between year 0 and 1 (Figures 1a and 1b). In summer of post-eruption year 2 and 3 (not shown) no pronounced signal is detected. The strongest, highly significant cooling signal (∼−0.5°C averaged over Europe) is found during the summer of year 1 after the eruption (Figure 1b). All 15 composite members show a cooling during this summer (not shown). This indicates a high robustness of the volcanic signal. The strength and homogeneity of this signal are remarkable, considering that it might be dominated or obscured by internal climate variability [e.g., *Xoplaki et al.*, 2005]. The temperature anomaly patterns show large spatial variability. The summer cooling is most pronounced (more than 1°C in year 1) and highly significant (99%) over northern and northeastern Europe. An area of weaker, yet significant negative temperature anomalies, extends further south into Central Europe and parts of the Mediterranean. In year 0 the summer cooling is somewhat weaker and confined to western Europe (Figure 1a). These findings for summer are in agreement with an observational study (eruptions back to 1875) by *Robock and Mao* [1995], though their observed mean anomaly pattern is somewhat less intense. The regional average European summer temperature signal compares well with previous observational studies [e.g., *Angell and Korshover*, 1985].

[10] Independent precipitation reconstructions [*Pauling et al.*, 2006], analysed for a subset of 10 eruptions after 1769 show low statistical significance for precipitation changes following eruptions. Generally they indicate a tendency to wet conditions over parts of the Mediterranean, as well as over northern Europe in post-eruption summers. A weak tendency to dry conditions over Central and eastern Europe is found in the summer of year 0 (Figure 1c) and year 1 (Figure 1d). However we expect the signal to be partly disturbed due to the large noise in the precipitation field.

[11] Changes in circulation are found in both the two post-eruption summers (not shown). However the signal is only robust in summer of year 1, showing a significant decrease in 500 hPa height centred over Finland. This suggests that there may be a summer circulation response to large tropical eruptions, which may reflect an atmospheric response to the local cooling maximum. This circulation change, will in turn, modify the directly forced response.

5. Winter Warming and Circulation Anomalies

[12] The winter temperature response to the 15 tropical eruptions covering the past half-millennium is clearly dominated by a strong warming over northern Europe in the first two winters after an eruption. Again, the winter temperature response is stronger in year 1 (mean ∼ +0.75°C; Figure 2b) than in year 0 (Figure 2a). We suggest that this time-lag, also noted in a GCM study by *Yoshimori et al.* [2005], is

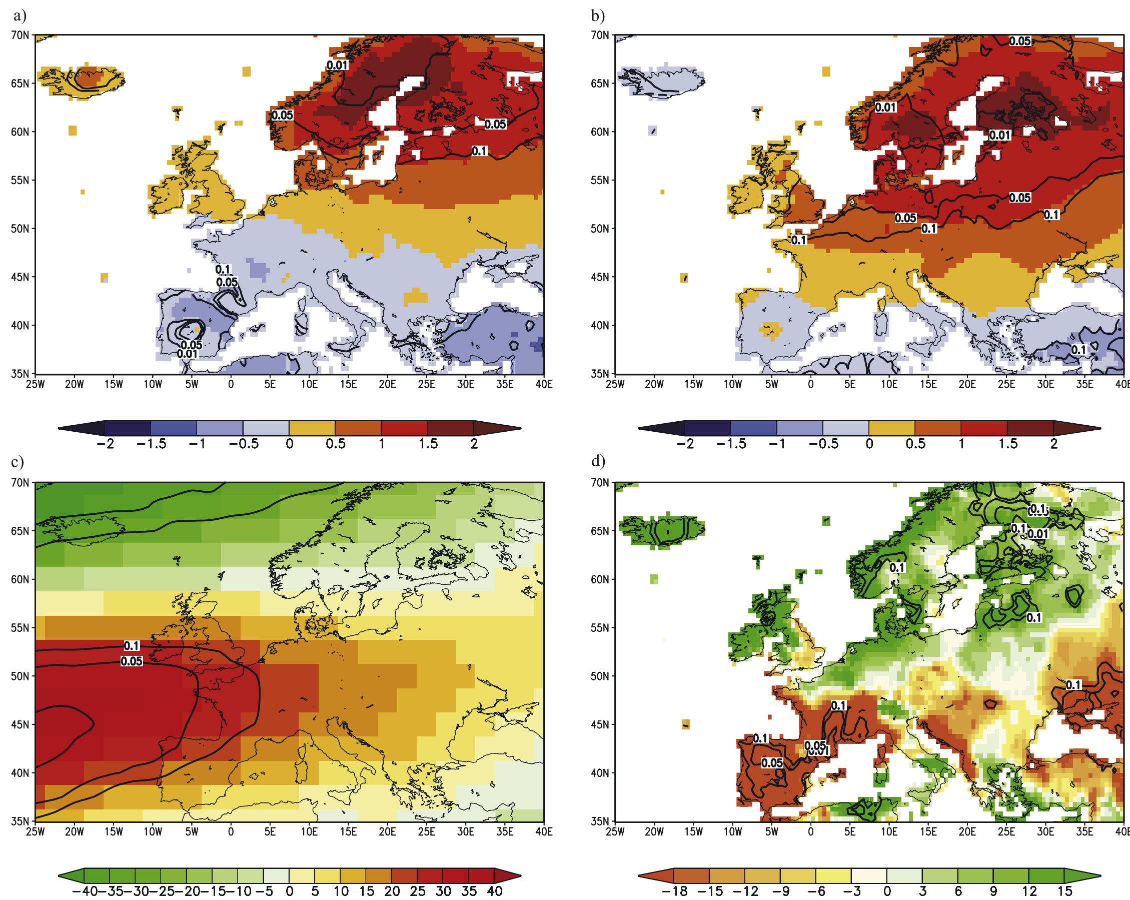

Figure 2. Anomaly composite of the European winter temperature [°C] in (a) year 0 and (b) year 1 following 15 tropical volcanic eruptions over the past half millennium. Anomaly composite of (c) the European winter 500 hPa geopotential height anomaly [gpm] and (d) winter precipitation [mm/month] in year 1 following 10 tropical volcanic eruptions over the past half millennium. The black contours mark the statistical significance as p-values (representing 90%, 95% and 99% confidence level) of the Mann-Whitney Rank Sum Test.

due to the time taken for the temperature gradient, which forces the dynamical winter response, to fully establish itself. The spatial anomaly pattern shows pronounced warming over northern Europe and weak cooling over southern Europe (Figure 2b). The positive temperature anomalies are most significant (more than +2°C) over Scandinavia and the Baltic area. The winter warming signal over northern Europe in year 1 is robust and is present for all eruptions, with the exception of Cosiguina 1835.

[13] The European winter anomaly patterns resemble those from observational studies covering the last 100–200 years [*Robock and Mao*, 1995; *Groisman*, 1992; *Kelly et al.*, 1996]. Furthermore, the temperature patterns compare well with cold season (October–March) anomalies presented by *Shindell et al.* [2004], based on a different set of large-scale proxy-based seasonal temperature reconstructions [*Rutherford et al.*, 2005]. It is important to note that the volcanic signal, particularly in winter, is robust only on relatively large spatial scales [*Písek and Brázdil*, 2006]. Similar NH winter warming patterns are also found in GCM studies [*Graf et al.*, 1994; *Kirchner et al.*, 1999; *Stenchikov et al.*, 2002, 2006; *Shindell et al.*, 2004]. These simulations suggest that the winter warming is caused by atmosphere-dynamical effects in form of a positive phase of the AO/NAO.

[14] Our analysis of independent 500 hPa geopotential height fields [*Casty et al.*, 2005] support these findings for 10 major tropical eruptions within the 1769–2000 period. Figure 2c reveals that geopotential height during two post-eruption winters is characterised by an enhanced north-south gradient, strongest over western Europe and the North Atlantic. This pattern, representing a positive phase of the NAO, is most pronounced in winter of year 1. This circulation anomaly pattern was also detected in simulations performed with different GCMs [*Stenchikov et al.*, 2002, 2006; *Yoshimori et al.*, 2005]. The change in post-eruption winter atmospheric circulation might largely account for the distinct temperature response. Additionally to the direct mid- and high-latitude circulation response to the stratospheric aerosols, there could also be a contribution of more far field processes. *Adams et al.* [2003] suggested that volcanic eruptions may be linked to an increased chance of El Niño warming in the Tropical Pacific. This may influence the NAO towards a negative state [*Brönnimann et al.*, 2007] and thereby counteract the direct NAO response to tropical eruptions. However, our results showing a positive NAO after large volcanic eruptions suggest this effect does not overwhelm the direct effect of volcanoes on the NAO.

[15] Independent precipitation reconstructions [*Pauling et al.*, 2006] indicate a tendency to anomalously wet conditions over northern Europe and dry conditions over the Iberian Peninsula and southeastern Europe in the winter of year 0 (not shown) and 1 (Figure 2d) following 10 eruptions (1769–2000). We suggest that this pattern is consistent with the aforementioned winter circulation anomalies following volcanic eruptions enhancing the advection of maritime air from the North Atlantic towards northern Europe. This indicates, that the precipitation response on regional and seasonal scale is complex and strongly dependent on circulation changes, while at global scale mean precipitation is reduced as a consequence of lower shortwave radiation [e.g., *Gillett et al.*, 2004].

6. Conclusions

[16] The analysis of independent, high resolution multi-proxy reconstructions provides new evidence for significant continental-scale summer cooling over Europe following major tropical eruptions. This direct radiative cooling effect is remarkably robust and found after all analysed major eruptions back to 1500. Significant winter warming over northern Europe is observed in year 0 and 1 following a major tropical eruption. This temperature anomaly is associated with a positive phase of the NAO, with stronger westerlies into Europe and a tendency to wet conditions over northern Europe. The consistency of signals across the 15 events studied here allows to a certain degree of confidence forecasts of seasonal temperature, circulation and precipitation anomalies over Europe after major volcanic events.

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